A Sea Floor Survey of the Sleipner Field to Monitor CO2 Migration

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ABSTRACT

In the North Sea natural gas production field at Sleipner, CO_2 is being separated from natural gas and injected into an underground saline aquifer, known as the Utsira formation, for environmental purposes. In this study, gravity measurements were made over the Sleipner CO_2 injection site in 2002 and again in 2005 on top of 30 concrete benchmarks on the seafloor to study the behavior and physical properties of the injected CO_2. As the gas is injected, pore space water is replaced by gas, altering the bulk density of the formation. This results in a change in gravitational acceleration observed on the overlying sea floor. Our gravity measurements show a repeatability of 4.3 μGal for 2003 and 3.5 μGal for 2005. Forward models of the gravity change are calculated based on both 3-D seismic data and reservoir simulation models from other studies. These forward models indicate that the magnitude of maximum gravity change is primarily related to CO_2 density rather than flow geometry. The time-lapse gravity observations best fit a high temperature forward model based on the seismically determined CO_2 geometry, suggesting that the 3-D reflection seismics are imaging the geometry of the injected CO_2, and that the *in situ* CO_2 density is around 530 kg/m^3. Uncertainty in determining the average density using this technique is estimated to be ±65 kg/m^3 (95% confidence), however, additional seismic surveys are needed before final conclusions can be drawn. Future gravity measurements will put better constraints on the CO_2 density and continue to map out the CO_2 flow.

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INTRODUCTION

The Sleipner Project is the world's first commercial application of emissions avoidance through the use of carbon capture and geologic storage technologies. The Sleipner field is a natural gas production area located about 240 km off the coast of Norway in the North Sea and operated by Statoil. In order for natural gas drawn from the site to meet commercial specifications, its CO_2 content must be reduced from about 9% to 2.5%. In gas fields worldwide, this excess CO_2 is typically vented into the atmosphere, but at Sleipner the CO_2 is compressed and injected into a porous saline aquifer known as the Utsira formation [1, 2]. The injection point is at a depth of 1012 m bsl and the water depth is about 80 m. Injection began in 1996 at a gradually increasing rate. Currently, about 1 million tons (MT) of CO_2 are being separated from the natural gas and injected into the Utsira formation each year.

Because CO_2 has never been compressed and injected in to an underground formation for environmental geologic storage, monitoring the injected CO_2 is used to confirm that it is safe and reliable. Time-lapse 3-D seismic surveys have been successfully employed to image the underground CO_2 [3, 4]. In this study, we use time-lapse seafloor gravity measurements to image and to put constraints on the *in situ* density of the CO_2.

EXECUTIVE SUMMARY

Our group at Scripps Institution of Oceanography has developed a methodology to make high-precision relative gravity measurements on the sea floor. The strength of Earth's gravity field at any particular location depends on the observer's position and the density of nearby rocks. If either of these changes in time, the value of gravity observed will also change. Therefore time-lapse gravity measurements provide a way to monitor density and shape changes in the Earth. Our measurements are precise to around 5 μGal (1 Gal is 1 cm/sec^2; the nominal value of gravity is around 980 Gal, so 5 μGal represents a fractional uncertainty of 5 parts per billion, and enables a sensitivity to height changes as small as 2 cm and to a mass change equivalent to an 8 cm thick layer of water).

A primary motivation for precise, repeated sea floor gravity measurements has been for reservoir monitoring in the oil and gas industry. As gas or oil are extracted from an underground reservoir, it is replaced by water normally. Because water density differs from that of gas or oil, gravity changes observed on the sea floor above a producing reservoir can help to construct a model of fluid movement in the reservoir. In collaboration with European geoscientists, we have applied this technique to study gas injection in a large CO_2 sequestration experiment in the North Sea.

At the Sleipner production well in the North Sea, natural gas is extracted which contains a significant fraction of CO_2. The CO_2 is separated from the hydrocarbon on the production platform, and—rather than being released into the atmosphere as would normally be done—it is pumped into an underground reservoir: the Utsira formation. The Utsira formation is a layer of sand several hundred meters thick about 1000 m below the sea floor with a huge lateral extent (hundreds of km). Impermeable shale layers cap the highly porous sand, making it an ideal reservoir.

The injected CO_2 maintains a gaseous form in the pressure/temperature conditions of the reservoir. However, while the ambient pressure is known, the temperature profile of the formation has not been accurately measured. This is important because the CO_2 density changes rapidly with temperature in the part of its phase diagram relevant to the Utsira depth/temperature regime. As a result, the density of the sequestered CO_2 is not well known. It could reasonably be in the range from 300 to 700 kg/m^3. Seismic imaging reveals the volume of CO_2 in the reservoir, but to know if the CO_2 is safely contained, we must know the mass of the CO_2 in the reservoir (because we know the mass that has been injected). To get the mass, we must know both the volume and density of the CO_2 "bubble" in the formation. In reality, it is somewhat more complicated than this because the porosity of the reservoir, the fraction of the pore water that is displaced, and the amount of CO_2 that becomes dissolved in the pore water all are factors in the model. These are all predictable at some level, but only gravity measurements can reveal the actual bulk density.

With funds from this DOE grant (and funds from the European CO2STORE group), we performed two gravity surveys over the Sleipner sequestration site: one in 2002 and a second in 2005. Each survey required about five days of ship time and a Remotely Operated Vehicle (ROV) to move the gravity sensors from place to place on the sea floor. The gravity changes accumulating between the surveys are attributed to the injection of CO_2. The first step was to install seafloor benchmarks. These are concrete platforms on which the ROV sets our gravity meters to facilitate accurate relocation of the observations from survey to survey. Thirty such benchmarks were installed on the sea floor in an array over the CO_2 injection point, and multiple gravity and pressure observations were made on each benchmark during both surveys. The gravity sensors used are commercially available mass-spring land sensors (made by Scintrex) installed in specially made seafloor housings (built as Scripps). The pressure gauges were quartz based (made by Paroscientific). Each benchmark was occupied three or more times for 20 minutes. The repeatability of these multiple measurements within one survey allowed us to estimate the uncertainties in the final gravity results. We encountered two unexpected sources of difficulty. The first was local motions of the benchmarks. In previous surveys we found that the positions of the benchmarks (each weighing several hundred kg) on the seafloor were stable at the cm level. However, in the Sleipner experiment, some of the benchmarks moved vertically between the two surveys by as much as 20 cm (we expect this was caused by storms and heavy currents). These vertical displacements affected the gravity differences, but fortunately, the displacements were easily apparent in our repeated sea floor water pressure measurements. These provided a means to correct the gravity observations for changes in observations height. The second source of unexpected difficulty was the gravity signal of the region from which natural gas was being extracted (where the bulk density is also changing). The signal, however, being derived from a much deeper formation, caused only a long-wavelength signal which was easily removed from our data.

The result of our surveys and subsequent analysis was a clear gravity decrease that developed in the time between the two surveys. A map of the gravity field decrease places the signal right on top of the CO_2 bubble. From the magnitude of the gravity change we infer that the in situ density of the CO_2 is fairly low (lower than had been originally assumed), indicating that the temperature of the reservoir is about 5 °C higher than had been originally assumed. This is in good accord with other temperature estimates that brought into question the single measured value that has been used in previous analyses.

The density estimate suffers from some uncertainties in the seismic models and imperfectly known reservoir parameters (like porosity and CO_2 saturation). Nevertheless, with the relatively brief interval between these first two surveys, we have demonstrated the utility of time-lapse gravity measurements in monitoring a CO_2 sequestration reservoir, and we have provided an important measure of the in situ density of the CO_2 (and therefore reservoir temperature). As future gravity surveys are made, the uncertainties in the results will decrease.

EXPERIMENTAL

Seismic monitoring of the Sleipner injection experiment has been underway for more than a decade. In addition to a pre-injection 3-D seismic survey obtained in 1994, 3-D seismic data were acquired over the Sleipner area in 1999, 2001, and 2002 (partial coverage of the CO_2 plume) by a European consortium of geoscientists. The results of the seismic surveys clearly show the geometry of the injected CO_2 [4]. By 1999, some of the CO_2 had reached the top of the Utsira sand and the plume has since been spreading both laterally and upwards from the lower levels towards the top of the formation. High amplitude sub-horizontal reflections are caused by accumulation of CO_2 under thin inter-reservoir shale layers [3-5], which act as temporary barriers to bouyantly driven CO_2 flow.

Arts et al. [6] and *Chadwick et al.* [5] made estimates of the CO_2 mass within the Utsira sand in 1999 using the seismically imaged volume. Assuming the density of CO_2 within the reservoir to be 700 kg/m^3 *Chadwick et al.* [5] estimated 2.01 MT compared to the known injected mass of 2.35 MT for 1999. In this model the CO_2 within the reservoir was partitioned between high saturation thin layers and a low saturation volume existing in a diffuse form between the layers. Evidence supporting the existence of diffuse CO_2 is given by *Chadwick et al.* [4]. Mechanisms such as dissolution of CO_2 into the formation water can help explain the difference in known injected mass and the estimation by *Chadwick et al.* [5]. However, one of the largest sources of uncertainty in estimates of CO_2 mass comes from uncertainty in the density of CO_2 within the Utsira formation. The density of CO_2 depends primarily on the temperature. The impact of impurities such as methane, BTX (butanes, toluenes, and xylenes), and vaporized water are neglected in this study [1].

A single downhole log measurement of 37 °C at a depth of 1058 m bsl [7] exists to constrain the virgin rock temperature profile through the Utsira formation. This measurement is subject to an uncertainty of several °C [8]. However, accurate reservoir characterization of the Sleipner East field, from 21 drill stem tests, give a reservoir temperature of 101.7 ± 0.5 °C at 2600 m depth [8]. By accounting for the differences in thermal conductivity of the rocks above this depth, the temperature of the Utsira Formation at 1058 m bsl is expected to be 42.5 °C. Near the predicted reservoir temperature and pressure conditions, CO_2 goes through a critical phase transition in which the density changes from 200 kg/m^3 to over 700 kg/m^3. Thus a slightly higher temperature could result in a much lower CO_2 density. Additionally, the CO_2 will be heated during compression from the wellhead conditions (25 °C, 64 bar) and down through the injection well. Because of the high injection rates, the injected CO_2 may experience close to adiabatic conditions, putting the temperature at a maximum of 57 °C at the bottom of the injection well. This could create an ultra-low density front or plume of CO_2 surrounded by cooler CO_2. Until recently, most of the work that has been done in reservoir simulations and in estimating the *in situ* CO_2 mass has assumed that the 37 °C measurement is correct, and that the CO_2 density is 650-700 kg/m^3. Therefore, determining the *in situ* CO_2 density is important for the long-term modeling and predictions.

As CO_2 is injected into the Utsira sand, it displaces the water from the pore space in the sand, causing an effective bulk density decrease within the formation. In this study, seafloor gravity measurements were made with an ROV carried instrument shown to be capable of measurement accuracies of 10 μGal or less [9-11], comparable to land surveys. The instrument used is the ROVDOG (Remotely Operated Vehicle deployable Deep Ocean Gravimeter), which contains three Scintrex relative gravity sensors [11]. Gravity measurements were made on top of concrete benchmarks, meant to serve as stable platforms to place the instruments in exact registration on the seafloor. The benchmark locations are shown in Figure 1. The first gravity survey was carried out from August 16-20, 2002. Each station was visited at least 3 times, to give adequate control on drift and survey accuracy. To aid with tide corrections, pressure was continuously recorded over the duration of the survey using portable seafloor instruments located at the center of the survey area. A total of four CTD measurements were made at benchmark SP09. The 2005 gravity survey was carried out from September 2-6, with each station visited at least two times. Reference tide gauges were deployed at benchmarks SP20 and SP9, and 11 CTD measurements were made.

After correcting gravity values for tides (using the tide model SPOTL [12]), instrument temperature, tilt, and drift, the uncertainty is 4.3 μGal in 2002 and 3.5 μGal in 2005 (Figure 2a). The uncertainty in the relative depth estimates is 0.37 cm for 2002 and 0.54 cm for 2005. Figure 2b shows the residuals after the mean value of a station is subtracted from each measurement at that station. Details of the pressure (depth) processing can be found in *Stenvold et al.* [13].

RESULTS AND DISCUSSION

Time-lapse results

Changes in gravity over time are found by subtracting the 2002 results from the 2005 results. A long-wavelength gravity trend increasing to the west can be seen, with a maximum value at benchmark SP01 of 30-40 μGal. The most likely source of this signal is from natural gas that is being produced from the Ty formation reservoir, which lies about 1.5 km below the Utsira formation and west of the injection point. Production from this reservoir is expected to cause an increase in local gravity due to a rise in the reservoir water as the natural gas is removed. A forward model was calculated based on Ty formation reservoir geometry, porosity, temperature, gas production data, and data from monitoring wells (all proprietary information), and matched to the gravity data.

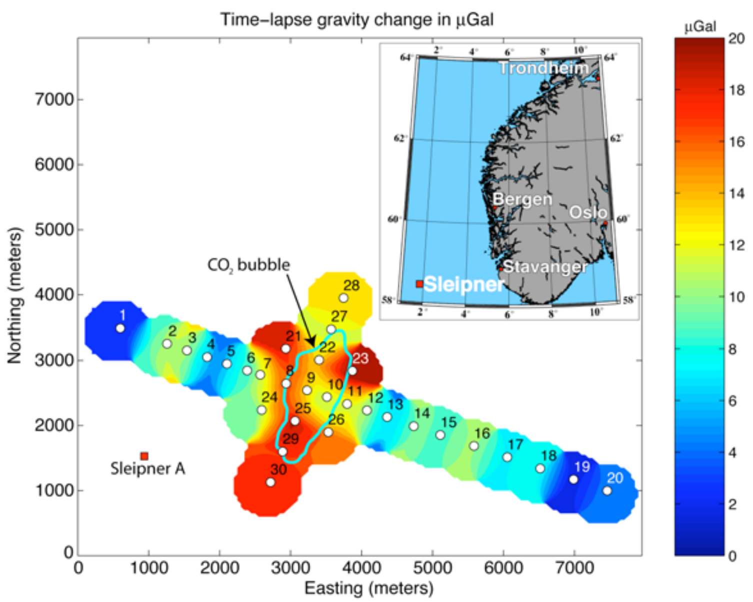

Figure 1. Benchmark locations are shown by white circles. The rim of the seismically imaged CO_2 bubble is shown as a blue line. The inset shows the location of the Sleipner platform with respect to southern Norway. Also shown is a smoothed version of the gravity residuals after correcting for depth and a long wavelength trend. Note the spatially coherent gravity change over the bubble.

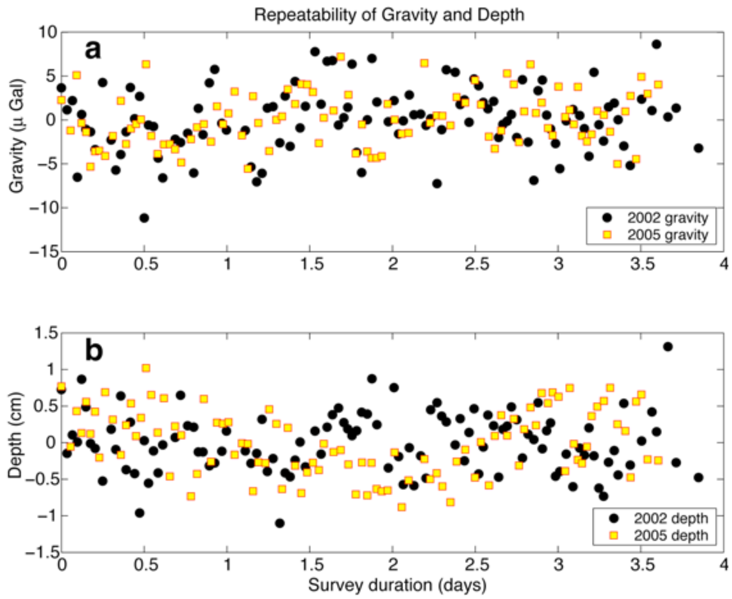

Figure 2. a) The scatter of repeated gravity measurements after the mean of each station has been subtracted from each measurement. Each point is the average of the three gravimeters. b) The scatter of repeat pressure measurements after the mean for each station has been subtracted. Each point is the average of the three pressure gauges. In both graphs, catter around zero is a measure of instrument noise in the survey because we expect no change in either gravity or depth during the several-day period of the survey (after correction for tides).

The time-lapse gravity (after the Ty forward model has been removed) and depth data are shown together in Figure 3a. The depth changes have a scatter of ~7 cm, with no apparent spatial correlation. Changes in the gravity coincide nicely with the changes in depth, providing assurance that the observed depth changes are real. These depth changes are most likely due to subsidence from sediment scouring around each benchmark. Sediment scouring is common in this part of the North Sea, especially in shallow water such as the Sleipner area, indicating that the benchmarks are not as stable as we had hoped.

The theoretical vertical gravity gradient in the ocean is 0.220 mGal/m (the free water gradient). The time-lapse gravity data were inverted to solve for a scale factor to the Ty formation model and the gravity gradient simultaneously. Gravity data from only the outer benchmarks were used, to remove the influence of the injected CO_2 from the inversion. Figure 3b shows the best fitting line to the dg versus dz data after the Ty formation model has been subtracted. The result is $dg/dz = 0.16 \pm 0.04$ mGal/m. This value is lower than the value of the free-water gradient. A combination of scouring and benchmark settling would decrease the gradient to between 0.182 and 0.155 mGal/m, depending on the amount of benchmark settling.

Figure 1 shows the resulting corrected time-lapse gravity values. Each point has been smoothed by averaging all observations within a 500 m radius of that point. The total time-lapse uncertainty in each gravity measurement is 5.3 μGal, and the uncertainty in each time-lapse depth change is 0.9 cm. A dip in the gravity with a maximum decrease of about 15 μGal can be seen in the data from an easting of ~2000 m to ~ 3000 m. This is the region of expected gravity decrease due to CO_2 injection. Benchmark SP3 (located at an easting of about 1000 m) also shows a dip in gravity. However, this is not spatially correlated with surrounding sites, suggesting that it is a spurious point. Benchmarks SP29 and SP30 are similarly low, suggesting spread of CO_2 to the south.

3-D forward modeling

The seismic data from 1999 and 2001 were used to build gravity forward models of injected CO_2 for two scenarios. The first is for an average CO_2 density within the reservoir of 700 kg/m^3, and the second is for an average CO_2 density of 550 kg/m^3. These correspond to low reservoir temperature (35 ºC) and high reservoir temperature (45 ºC) scenarios, respectively. These models contain supercritical CO_2 in two distinct parts. The first is CO_2 residing in thin, high saturation layers, which have ponded beneath thin inter-reservoir shale layers. The second is a low saturation diffuse volume occupying the space between the high saturation layers. The high-density model predicts a maximum change between 1999 and 2001 of about 2.7 μGal/year, while the low-density model predicts a maximum change of about 4.5 μGal/year. Additionally, reservoir flow models were built by SINTEF, an independent research organization, to model CO_2 migration and accumulation. The models incorporate features seen in the seismic data, and are used to predict CO_2 migration and accumulation from 2002 until 2005, when no seismic data is available. These models are post-processed to model the gravimetric response on the seafloor. Again, both low reservoir temperature and high reservoir temperature scenarios

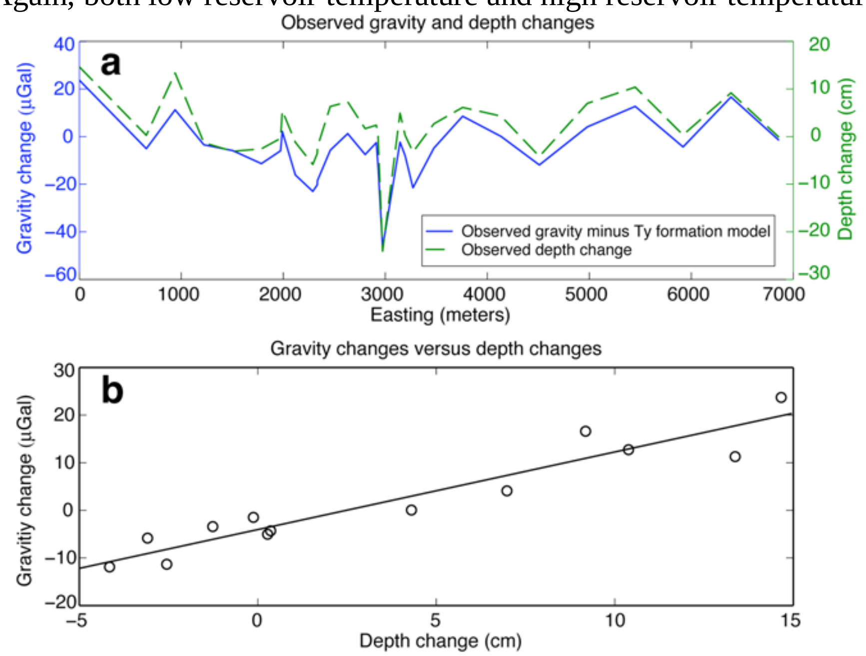

Figure 3. The correlation between depth changes and gravity changes is shown in two ways. a) Variations in gravity correlate with changes in depth, and appear to be randomly distributed. b) Gravity changes are plotted against depth changes for the outermost benchmarks. The slope of the best fitting line is the gravity gradient (0.161 mGal/m). See the text for details.

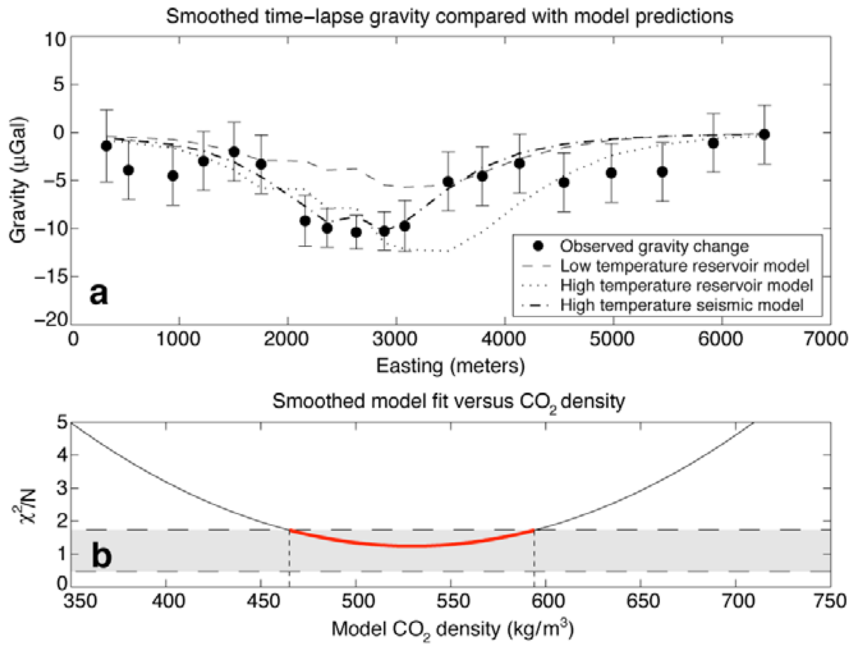

Figure 4. a.) Smoothed time-lapse gravity change plotted along with predicted gravity change for high (average CO_2 density of 550 kg/m^3) and low reservoir temperature (average CO_2 density of 700 kg/m^3) models. Both the models and the observations have been smoothed by averaging neighboring values. Observed gravity changes are most similar to the high temperature seismic model. b.) Model misfit (χ^2) normalized by the number of measurements (N = 19) is plotted against model CO_2 density for the seismic models. A minimum misfit occurs at a density of 530 kg/m^3 with a 95% confidence interval (grey box) of ± 65 kg/m^3.

were generated. They produce a gravity decrease of 2.2 to 2.4 μGal/year for a CO_2 density of 700 kg/m^3 and 4.7 μGal/year for a CO_2 density of 550 kg/m^3, similar to the models based on seismic response from 1999 to 2001 [14].

CONCLUSION

For a given Utsira temperature, reservoir simulations predict gravity changes that are on the same order of magnitude as pre-2002 seismic models. This insensitivity to detailed flow geometry suggests that the magnitude of the maximum time-lapse gravity signal is due primarily to CO_2 density. Figure 4a shows a smoothed version of the forward model predictions and the observed gravity. The smoothing was done by averaging each point with its nearest neighbors to the east and west. Three points from about 2200 to 3200 m easting include the nearby points off the northwest-southeast trending main line, so that all the time-lapse gravity information is collapsed onto a single line. The error bars for this plot were calculated as the time-lapse uncertainty (5.3 μGal) divided by the square root of the number of points included in the average. The difference in the shape of the reservoir models and seismic model reflects the differences between the CO_2 flow geometries. The flow in the idealized reservoir simulation models is simplified and has a much larger westward component than the seismic data indicate. The maximum difference between the high and low CO_2 density models is about 7 μGal, which is very close to the 5.3 μGal uncertainty in each measured value, however, by smoothing the data and models, observations fit the high temperature seismic model the best. Linear extrapolation of the smoothed seismic models to include a wide range of CO_2 density suggests that the CO_2 has an average density of about 530 kg/m^3. 95% confidence intervals of average density are estimated to be ±65 kg/m^3, from the χ^2 fit of the smoothed data, demonstrating the resolving power of this technique. However, this estimate does not include uncertainty in the models, including uncertainties in the seismic data, uncertainties in determining CO_2 saturation from seismic pushdown, and unknown flow geometry from 2002 to 2005. In another few years, as signal levels increase and new seismic data is acquired, more confidence can be placed on the density estimate

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